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Deformation and Compression Behaviour of a Cement–Bentonite Slurry for Groundwater Control Applications

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Abstract Cement bentonite (CB) barriers are self-supporting, low permeability, structures used to retard groundwater flow and as such strength and hydraulic conductivity parameters are often stipulated when developing the mixtures. This paper reports an investigation into the deformation and compression behaviour of a CB containing ground granulated blastfurnace slag using the unconfined compressive strength apparatus, triaxial (undrained, unconsolidated) and oedometer. Samples were also exposed to drying and rewetting to investigate possible response to changes in environmental conditions. Cracking was observed prior to peak stress suggesting that the hydraulic conductivity of a barrier may be adversely affected before the shear strength is reached in undrained conditions. The compression response of CB indicates the presence of a threshold stress; once exceeded the magnitude of settlements are significantly greater than those encountered below this threshold. If a barrier experiences localised changes

in loading conditions then there is the potential for damage from induced differential settlements; thus it is recommended that the threshold stress should also be considered at the design stage in addition to strength and hydraulic conductivity requirements. The response of the material exposed to drying-rewetting was unexpected and requires further investigation to determine how a barrier will respond to changing environmental conditions.

Keywords Cement–bentonite · Low permeability barrier · Deformation and compression behaviour

1 Introduction

Cement–Bentonite (CB) low permeability cut-off Barriers (CBB) offer the means to retard groundwater flow and have been used to retard contamination plume migration, prevent salt water ingress, renovate aging geotechnical structures (such as in earth dams) and protect deep excavations from flooding. To achieve these roles the hydraulic conductivity of CBB must be very low and the ICE's (1999) specifications (for installations within the UK) require that this must be 1×10^{-9} m/s or less. Strength criteria are also specified by the ICE (1999) to ensure that the CBB can withstand deformation without compromising the performance of the barrier.

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Only considering strength and hydraulic conductivity properties of a CB may not provide sufficient information to determine material response, therefore this study investigated a CB containing Ground Granulated Blastfurnace Slag (GGBS), cement, bentonite and water, on the Unconfined Compressive Strength (UCS) apparatus, the triaxial (undrained, unconsolidated, TX-UU) and the oedometer. In addition a small study was undertaken in parallel with the main programme to investigate how the material responded to drying-rewetting in various situations. The findings from this investigation have been compared to the findings from other studies investigating CB to further understanding of CB behaviour.

2 Sample Preparation

2.1 Creation of the CB Slurry Mixture

The cement–bentonite mixture investigated comprised 40 g of Berkent 163 bentonite (supplied by Tolsa UK Ltd), and 200 g of cementitious materials for every 1000 g of water (produced in the laboratory using reverse osmosis, RO). The cementitious materials were a Rugby cement (CEM II/B-V, 32.5 N) and GGBS, supplied by Hansen Aggregates; 80% of the cement was replaced with GGBS (based on the recommendations of Garvin and Hayles 1999, and Opdyke and Evans 2005). The slurry was prepared in commercially available food mixers before being decanted in plastic cylindrical moulds (50 mm internal diameter by 150 mm in height for UCS-TX-UU samples and 75 mm internal diameter moulds for testing in the oedometer) to form bulk samples (following the procedure used by Royal et al. 2013). The bentonite powder was mixed into the RO water (for at least 20 min) and allowed to hydrate for 24 h; the cement and GGBS were subsequently added to the hydrated bentonite slurry and mixed for a period of 5–10 min; the slurry was decanted into the moulds (which were agitated on a vibrating table to remove bubbles of air); and the moulds were sealed with flexible plastic covers and stored in water. The samples were cast to be longer than required to prevent imperfections that develop in the upper face during curing (bleed, etc.) impacting on the samples during testing, these were trimmed prior to testing. After 7 days of curing the bulk samples were removed

from their moulds and stored under water (RO quality) until required for testing.

2.2 Potential Chemical Interactions Within CB During the Time Periods Considered

2.2.1 Curing of the Cementitious Materials

CB mixtures normally include cement replacement materials (commonly GGBS or Pulverised Fuel Ash, PFA) in order to achieve the performance specifications (notably the hydraulic conductivity). GGBS and PFA vary from Ordinary Portland Cements, OPCs, in chemical composition, and potentially size range of particles; depending upon the processing these material experience during manufacture. The notable compositional differences being the quantities of calcium oxides, aluminium oxides and silica oxides, (generally GGBS and PFA have increased levels of aluminium and silicon oxides and reduced quantities of calcium oxides when compared to OPC: Hill and Sharpe 2002; Escalante-Garcia and Sharpe 2004; Gao et al. 2005) resulting in changes in the Si/Ca ratio and thus impacting upon the products formed during curing (Hill and Sharpe 2002; Escalante-Garcia and Sharpe 2004; Gao et al. 2005). GGBS is considered a latent hydraulic binder (Hill and Sharpe 2002); the GGBS particles would experience curing reactions at both the outer surface and within the particles (also observed by Escalante-Garcia and Sharpe 2004). Conversely, Class F PFA (which does not contain significant quantities of lime; Gebler and Klieger, 1986) is considered a pozzolan, i.e. requires the presence of alkali conditions before it will hydrate (Hill and Sharpe 2002); normally initiated with the formation of Portlandite, through the hydration of the cement (Alite: Hill and Sharpe 2002) and curing reactions predominantly occur at the outer surface of the particles (Escalante-Garcia and Sharpe 2001).

Escalante-Garcia and Sharpe (2004) observed that the products associated with curing of GGBS particles varied with location: internal reactions were affected by the increased levels of aluminium and silicon resulting in formation of compounds like Hydrotalcite; external reactions included formation of calcium silicate hydrate (CSH) gels, Ettringite (AFm) and Hydrotalcite-like phases. However, Escalante-Garcia and Sharpe (2004) note that at 10 °C the dissolution-precipitation reactions at the outer boundary of the

GGBS particles dominated the internal reactions as the material cured, suggesting that the GGBS behaved as a pozzolan at this temperature. This finding was reinforced by the lack of Portlandite, and increased levels of Ettringite (AFm phase), in the hydration products cured at 10 °C, when compared to those formed at higher curing temperatures. Escalante-Garcia and Sharpe (2001) observed that PFA particles only experienced curing reactions at the outer surface of the particles, forming: CSH, calcium aluminium silicate hydrate (CASH) and Ettringite (AFm and AFt phases) and, at 10 °C, Stratlingite. The temperature of shallow subsurface soil deposits (<15 m) within the UK are considered to be a function of the atmospheric temperature (mean annual air temperatures approximately range between 8 and 12 °C) (Busby 2016), therefore the pozzolanic behaviour of the GGBS observed at low curing temperatures (10 °C) by Escalante-Garcia and Sharpe (2004) may well dominate the curing process of CB in shallow barrier installations within the UK.

The chemical composition of the CSH and CASH formed by both the cement-GGBS and cement-PFA blends can clearly be expected to vary from those of OPCs due to the differences in aluminium, calcium silicon oxides. However if sufficient quantities of GGBS are incorporated into the cementitious materials then the size and shape of the products formed can also be affected. Richardson and Groves (1992) observed changes in the structure of the CSH formed in hardened cements pastes that contained high levels of GGBS (70% or greater); the products were finer and more “foil like” when compared to the “fibrillar” structure more commonly associated with CSH formation with OPC. It is suggested that this change in physical structure of cementitious products, as well as the chemistry of the products, associated with the inclusion of significant proportions of GGBS that results in considerable variation in physical properties when compared to other CBs containing PFA (Royal et al. 2013); as illustrated in the range of physical response presented below.

2.2.2 Clay-Cement Interactions

The chemical nature of the hardened slurry (ignoring inherent changes due to curing of cementitious material) is unlikely to remain constant with time as both the precipitates from the cementitious reactions

and the bentonite (the smectitic minerals and any secondary minerals such as quartz, etc.) are vulnerable to degradation via dissolution-precipitation reactions in certain chemical environments. The cementitious products (Portlandite, CSH, CASH, etc.) are chemically stable at high pHs but will dissolve and reform as other products with reducing pH: Portlandite will degrade below a pH of 12.4 and the CSH gel will degrade below a pH of 10 (Gaucher and Blanc 2006). For example, Rimmele and Barlet-Gouedard (2010), who exposed various concrete samples to fluids supersaturated with carbon dioxide (driven into the concrete samples using electrokinetics, thus reducing the pH of the pore fluid), observed dissolution of the CSH, due to decalcification, and precipitation of carbonates associated with penetration of the dissolved carbon dioxide. Conversely, the smectitic minerals within the bentonite are likely to experience degradation at higher pH levels (Gaucher and Blanc 2006).

Much of the research considering chemical interactions between cements and smectitic clay soils have focused on the use of clay and concrete structures to contain hazardous materials, such as radioactive or toxic wastes. In these applications (radioactive and hazardous waste containment) the clay and concrete are likely to be separate structures that are adjacent to one another and the diffusion of high alkalinity waters/ions from the cement into the clay are the driving forces that induce changes in the smectitic soils. In addition, the temperature of the environment is often considered to be elevated due to the nature of the contained waste (for example temperatures adjacent to buried canisters containing radioactive waste might be expected to reach 70 °C; Pusch et al. 2011), thus accelerating reaction rates (Gaucher and Blanc 2006). This varies from conditions associated with CBBs, although the findings from this body of research may help to understand the chemical interactions taking place in CB.

Gaucher and Blanc (2006) undertook a review of the literature concerning cement-clay interactions (also see Pusch et al. 2003; Savage et al. 2002, 2007; Watson et al. 2009) and suggest degradation of smectitic minerals could be expected to follow a sequence of changes; the rate of these changes was found to increase if pH exceeded 11, although once the pH was above 13 the acceleration of degradation increased significantly. Pusch et al. (2003) suggest that

the critical pH for the degradation of smectitic minerals is 12.6 and chemically unaltered CB has been quoted as having a pH around 12.0 to 12.9 (varying with duration of curing, materials used, etc.) (Jefferis 1996, 2008). The sequence of smectitic mineral degradation is stated as: change in mineral structure (illitization or beidellitization); followed by zeolite formation (commonly Phillipsite and Analcime, depending on sodium levels within the pore fluid), and/or Saponite or Hydrotalcite if magnesium is present; and finally dissolution of the clay minerals with precipitation of CSH and CASH gels (Pusch et al. 2003; Gaucher and Blanc 2006). The stability of the products formed during these phases of dissolution and precipitation are a function of the pore chemistry, for example Savage et al. (2007) notes that the stability of the zeolites are a function of silica activity within the pores. Secondary minerals, such as quartz, feldspar and mica, can also degrade to form zeolites or CAS/CASH products, such as: Tobermorite, Hillebrandite, Foshagite and Hydrogrossular (Gaucher and Blanc 2006; Savage et al. 2007). The dissolution-precipitation front within the soil can be identified at the magnesium, aluminium, silicon rich zones within the clay (Gaucher and Blanc 2006). Watson et al. (2009) note that precipitation of products caused by reactions within the clay can reduce the pore spaces, reducing the volume in which the alkaline fluids (or ions) can migrate through; thus having a limiting effect upon subsequent reactions deeper into the clay later from the clay/cement interface. Pusch et al. (2003) investigated the chemical changes in an Illite-Montmorillonite dominated clay soil and noted that at 90 °C the clay samples had experienced zeolite formation after a few months exposure to the cement water. Plee et al. (1990), and Gaucher and Blanc (2006), note that the chemical degradation of the smectitic minerals occurs at the edges of the particles (rather than across the entire surface area), with the aluminates, silicates and functional groups dissolving in the alkali environment. The release of ions into the pore fluid with the dissolution of the minerals will produce a buffering effect on these reactions, as will the presence of dissolved carbon dioxide (Gaucher and Blanc 2006), which could reduce the pH within the pore. The rate of dissolution of the smectitic minerals when adjacent to a concrete is a function of three controlling factors: the nature of the pore, i.e. its chemistry (which may be in flux due to penetration of alkali fluids into the pore of

the clay, buffering of the pH with dissolution of minerals or penetration of dissolved carbon dioxide, etc.) and the degree of saturation; mass action within the pores; and temperature of the system, with increased temperature accelerating the rate of chemical reactions (Gaucher and Blanc 2006).

The chemical interaction between components of a CB slurry is likely to vary from the cement-clay interactions reported above as the bentonite is thoroughly mixed with the cementitious materials; hence it could be expected that much of the clay within the barrier will be susceptible to chemical reactions as the processes are not related to movement of alkali fluids (or ions) into the clay. The relatively small quantities of dispersed bentonite particles (commonly 3–6% by mass of water) within these barriers suggests that degradation to form zeolites or CSH/CASH compounds could occur relatively quickly (compared to natural clay deposits with denser particle packing arrangements); Joshi et al. (2008) report not being able to detect bentonite in mature CB (11 years old) using x-ray diffraction (XRD) and Jefferis (2008) was only able to detect “trace” amounts of calcium bentonite after 6 months curing (again using XRD).

Jefferis (1996, 2008) noted that the pH of CB sample could reduce (towards neutral) with the seepage of multiple pore volumes of water through them; with the flow of approximately 200 pore volumes of water through a CB sample the pH was observed to reduce to a value below 8 (the pH was approximately 12.9 at the start of the test and had fallen to approximately 11 after the permeation of 100 pore volumes of fluid; Jefferis 2008) in so doing the cementitious products may become vulnerable to dissolution and precipitation as other compounds (as noted by Gaucher and Blanc 2006). Jefferis (1996) noted that the hydraulic conductivity of the samples were observed to fall with increasing pH, suggesting that it could be due to precipitation of calcium carbonates, and that the material softened during the process. Jefferis (1996) also investigated a sample stored underwater for 15 years and found that the sample had experienced the leaching and carbonation (associated with the permeation of water, as encountered above) and thus had a pH around 9 prior to the commencement of testing.

The seepage of a hundred or more pore volumes of water through a section of a CBB, with an hydraulic conductivity of 1×10^{-9} m/s or less, could be expected to take a significant period of time (or

require a very large hydraulic gradient acting over the barrier, or a combination of the two) and thus this seems unlikely to be a significant factor in the chemical nature of competent CBB in the short term. However, if a sample submerged in water experienced similar changes in pH to those exposed to seepage of multiple pore volumes then potential interface between the barrier and surrounding soil may need to be considered; such changes may result in diffusion of ions from the previously unaffected volume of the barrier towards the edges (again this process would be slow), which could also have an effect upon the long term performance of the CBB. In addition, if the CBB contained weaknesses within the fabric (cracks, host soil incorporated within the hardened slurry due to poor quality assurance practices during construction, etc.) that resulted in localised increase in the hydraulic conductivity then the potential for preferential flow pathways through these zones could conceivably result in a reduction of the pH with groundwater flow, initiating dissolution of the cementitious products, potentially weakening the surrounding material and exacerbating the problem within the barrier.

2.3 Experimental Methodology

2.3.1 Testing in the UCS, Triaxial and Oedometer

Samples were prepared for testing (following the methodology by Royal et al. 2013) on the UCS and TX-UU, by placing them in a split mould (100 mm in length), which was secured in a simple jig, and shaving away the protruding length of CB using various saws and pallet knives. This produced samples with perpendicular faces and a length to diameter ratio of 2:1. A similar approach was used when preparing samples for investigation in the oedometer; the sample was extruded from the mould into the cutting ring and the sample was trimmed to fit.

The UCS and TX-UU tests were undertaken at a rate of displacement of 1.2 mm per minute on samples that had cured for 7, 14, 28, 60 and 90 days. CB samples batched from slurry are likely to exhibit a range of physical properties due to differences in material composition within the slurry (ICE 1999; Jefferis 2012; Royal et al. 2013). Therefore, the procedure described in Royal et al. (2013) was used: at least three samples were prepared for each test (the numbers of samples investigated in each test are

Table 1 Summary of experiments undertaken in the UCS and triaxial: number of samples investigated with confinement and curing period

7 days	14 days	28 days	60 days	90 days
<i>0 kPa confinement</i>				
6	5	9	5	3
<i>50 kPa confinement</i>				
6	6	4	5	4
<i>100 kPa confinement</i>				
5	6	4	4	3
<i>200 kPa confinement</i>				
5	5	5	5	4

presented in Table 1) and the mean behaviour of these samples was used to consider changes in deformation behaviour. Similar approaches were previously used by Opdyke and Evans (2005) and Williams and Ghataora (2011).

Consolidation tests were undertaken in the oedometer at 7, 14, 28 and 60 days, applying a range of loads up to 3200 kPa, following the method described in the British Standards (BSi 1990a) (having defined the specific gravity, G_s , of the CB as 2.57, using the small pycnometer method described in the British Standards BSi 1990b). Once again more than one sample was investigated (with the exception of the 7 day CB) and the mean of the behaviour reported herein. To define the one dimensional compression response multiple load steps are required, this highlights a limitation with the use of the oedometer to characterise the compressibility of comparatively young CB samples as its physical properties are changing with curing throughout the test (which can take several days, unlike UCS or TX-UU tests where it is assumed that the samples will not change significantly during the duration of the test). Therefore, the compressibility parameters derived using this method will be approximate until the rate of change in physical properties with curing has reduced with time (for this reason only a single 7 day sample was investigated to provide an indication of how juvenile CB behaves).

2.3.2 Drying (and Rewetting) of CB

When samples were removed from storage for preparation and testing they were dark green in colour (when cast they were grey); exposure to the air would

result in a gradual lightening in colour. Empirical evidence suggests that samples exposed to air would experience structural changes with loss of water, including: discolouration (changing from dark green to a very pale blue tinged light grey, Fig. 1a); formation of shrinkage cracks on the surface as they dried (Fig. 1b); widening (and intersection) of these cracks with continued drying, in so doing material would spall from the samples; this process would continue until the sample completely disintegrated (Fig. 1c). A different CB was investigated, in a related study, which did not contain GGBS (this mixture design used the same proportion of total cementitious materials, cement type and proportion of bentonite per litre of water as that herein) and the response to drying of this CB mixture varied with that containing GGBS. Figure 1d illustrates that the samples without GGBS (note that this material did not change colour with curing) did not (noticeably) exhibit surface cracking with drying and did not disintegrate. These samples could be handled (carefully) without causing visible damage, although drying produced a very lightweight, weak and friable material that would break into large pieces when cut with a hand saw (Fig. 1e). It is suggested that difference in behaviour between the two mixtures is a function of the physical structure of the cementitious products formed with curing (as described in Sect. 2.2.1). To limit the potential impact of this mechanism on the recorded behaviour, the

majority of samples were only removed from storage immediately prior to preparation and testing.

To investigate the changes in sample behaviour with drying, three small-scale experiments were undertaken on the CB containing GGBS. The first test involved drying the samples in an oven (at approximately 105 °C) for periods of 30, 60 and 90 min before investigating deformation response on the UCS (alongside samples that had not been dried prior to testing). Additional samples were rewetted after oven drying (submerged in water for 3 days) before being deformed on the UCS. Drying the samples in the oven provided a rapid means to reduce the water content within the samples but this is unlikely to reflect conditions in situ (unless exposed to a high temperature environment; for example the containment of radioactive waste referred to above). Therefore additional samples were allowed to dry in ambient conditions: some of these samples were subjected to cycles of drying and rewetting to determine if the samples would rehydrate after desiccating. Finally a number of samples were partially buried in saturated sand to determine if this impacted upon the drying of the samples. Two depths of burial were investigated: 50 and 20% of the sample length, with the remainder exposed to the atmosphere. The water level in the sand remained constant as the samples were exposed to these conditions for 28 days.

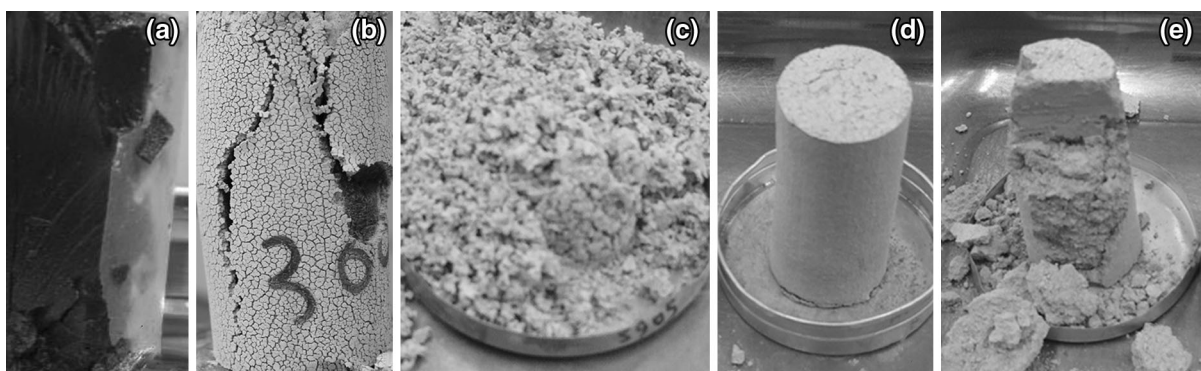


Fig. 1 Changes in structure of cement–bentonite samples due to drying. **a** Section of a 90 day sample, containing GGBS, which has only been exposed to ambient conditions for a short period whilst the sample was trimmed and tested in TX-UU (image reproduced in Fig. 5h). **b** Sample containing GGBS, exposed to cycles of wetting and drying before being investigated on the UCS, note drying and cracking of outer

surface resulting in spalling of surface material when deformed on UCS. **c** Sample containing GGBS was completely dried in the oven and as a result it disintegrated. **d** Sample without GGBS completely dried in the oven, it did not experience significant colour change (formed a grey coloured material with curing) nor did it disintegrate upon drying. **e** Fragmentation of the dried sample (without GGBS) when cut with a hand saw

3 Observed Deformation and 1D Compression Response

3.1 Changes in Deformation Behaviour with Curing and Confining Pressure

The anticipated non-linear increase in both strength and stiffness with duration of curing was observed on both the UCS and TX-UU, as was the expected variation in response associated with material cured from slurry (Figs. 2, 3). The majority of samples exhibited a notable peak deviator stress (even after

only 7 days of curing, which was not the case with samples containing PFA as the cement replacement material, where an obvious peak was not apparent until at least 28 days of curing, Royal et al. 2013), with strain softening after this threshold (Fig. 3). There also appears to be a slight reduction in mean strain corresponding to mean peak deviator stress with duration of curing, although this relationship is not as clearly defined as those for mean peak deviator stress and mean stiffness. It is evident that the inclusion of the GGBS within the CB produced significantly stronger and stiffer samples than those

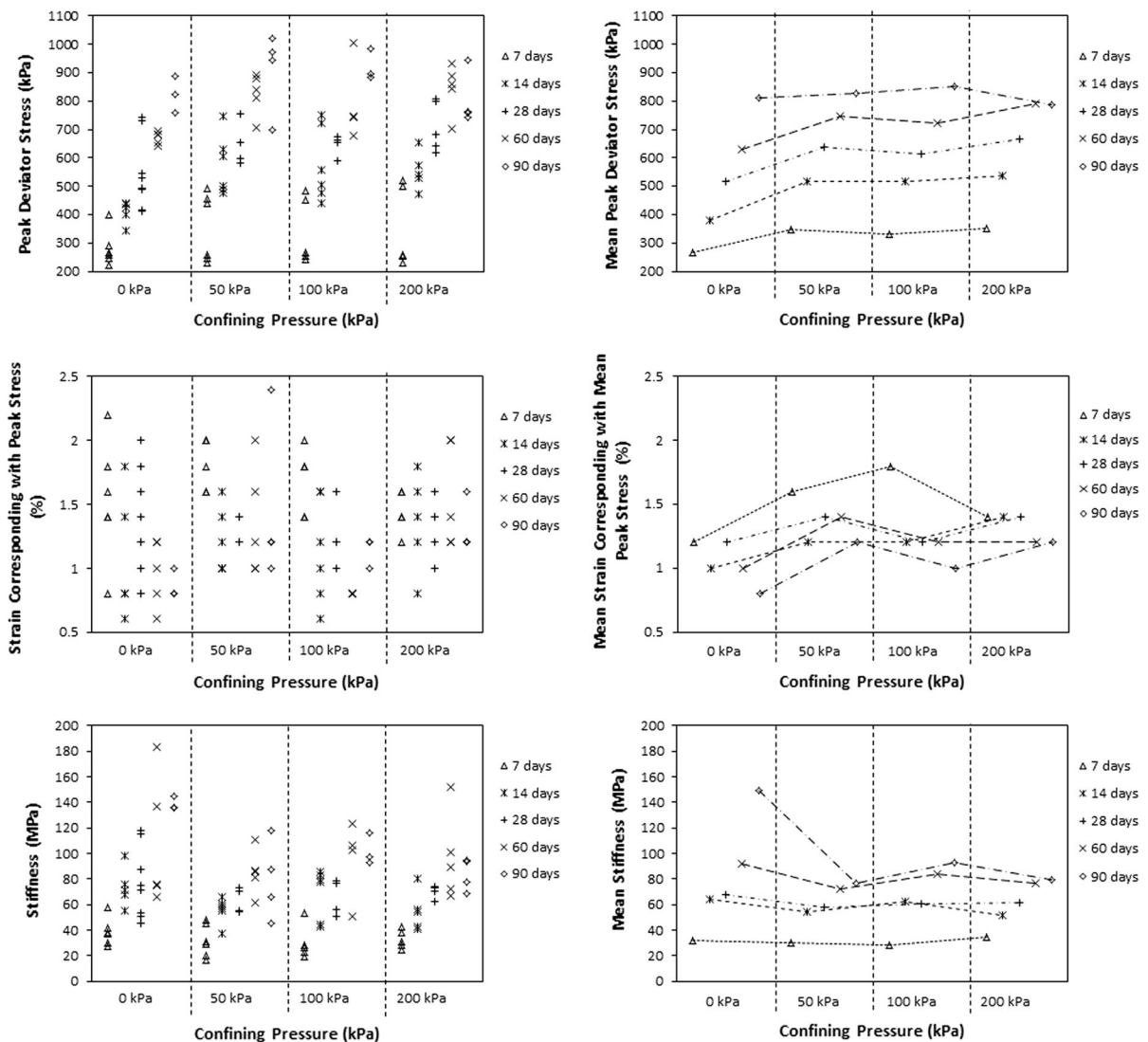


Fig. 2 (Left) Peak deviator stresses, corresponding strain for peak deviator stress and stiffness for individual samples and the (right) mean behaviour for the curing periods and four confining pressures considered

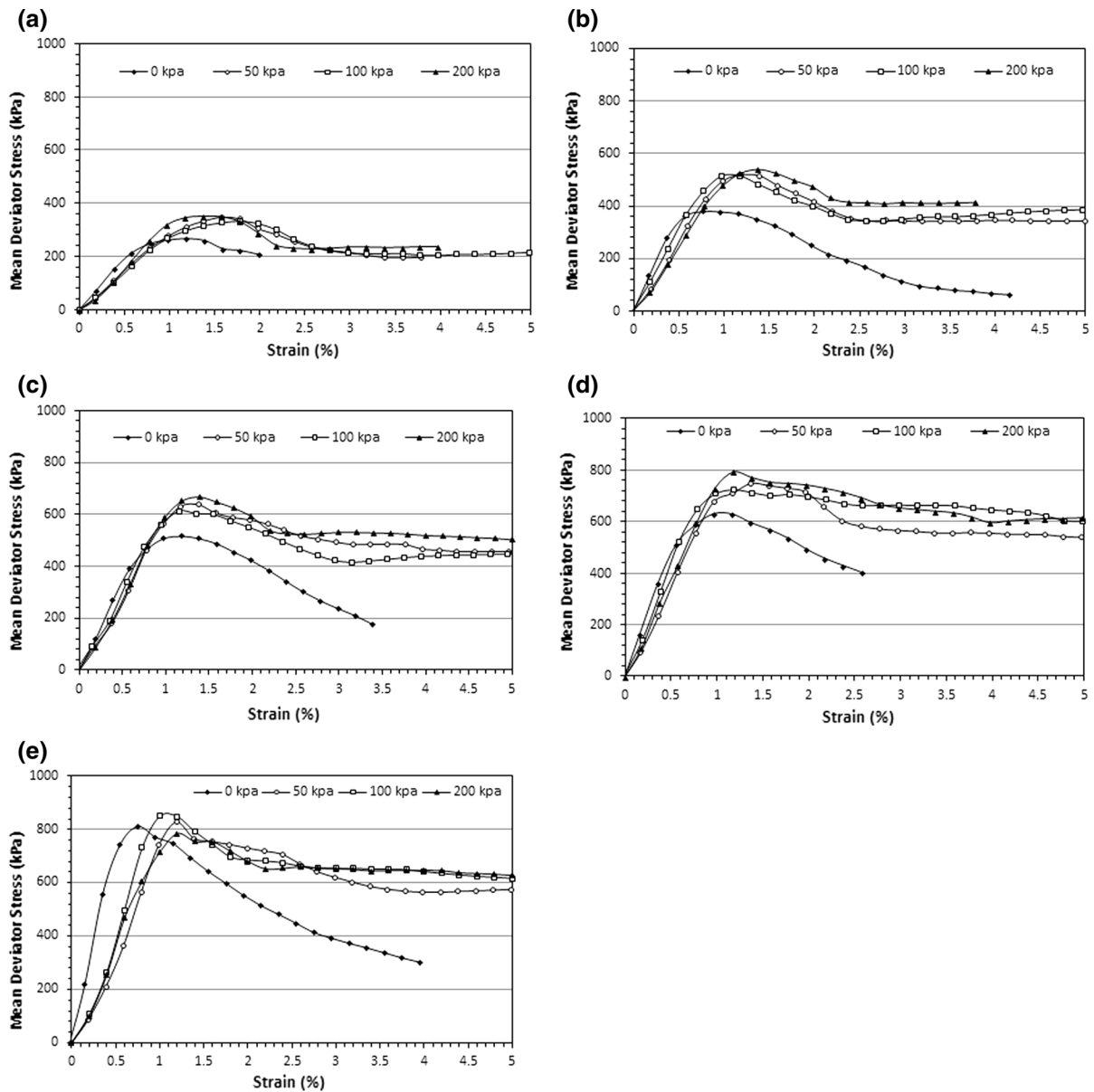


Fig. 3 Mean behaviour of cement–bentonite samples for the curing periods of: **a** 7 days, **b** 14 days, **c** 28 days **d** 60 days and **e** 90 days

containing PFA (Fig. 4; PFA data represent the mean values for all samples investigated by Royal et al. 2013 at the corresponding curing period/confining pressure; the GGBS data was previously presented in Fig. 3). It is suggested that this significant difference in physical properties is due to the types and physical structures of the cementitious products formed during curing (i.e. the GGBS producing a finer, foil like structure; Richardson and Groves 1992).

The majority of the samples investigated failed via the formation of a cone, or wedge, below the base of the load cap with deformation, resulting in the development of longitudinal tension cracks running approximately parallel to the axis of the cylindrical samples (Fig. 5A). Occasionally localised spalling of material from the outer surface of the samples would accompany the tension cracks. These tension cracks would widen with increasing deformation post peak strength. Post-test examination of the samples

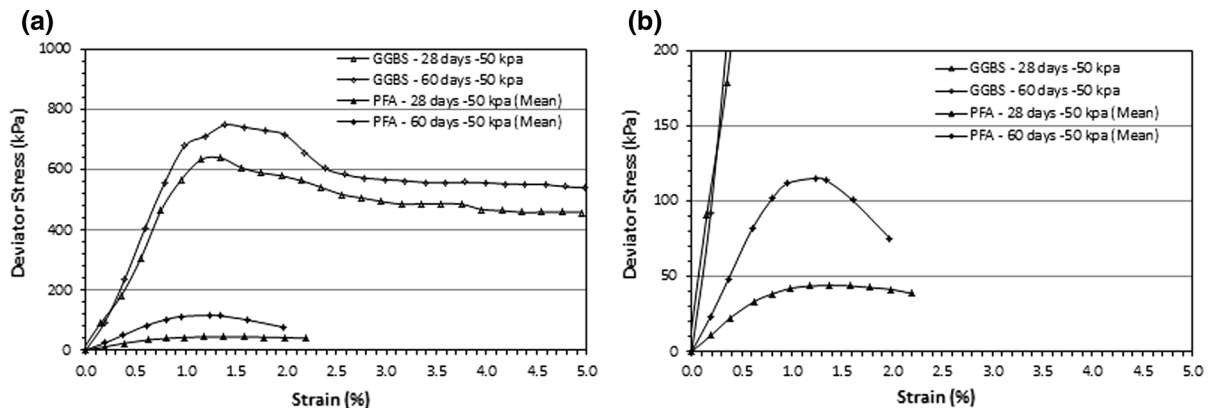


Fig. 4 Comparison of CB containing GGBS and PFA (both mixtures containing the same proportions of cementitious materials and bentonite). **a** Mean behaviour for the curing periods of 28 and 60 days at 50 kPa confining pressure. **b** Focusing on the behaviour of the samples containing PFA

illustrated the development of multiple internal shear planes, cleaving the sample into large fragments (with tension cracks occasionally developing within some of these fragments). Cracking was not observed in the triaxial during testing (due to the presence of the latex membrane) but on examination of the samples post-test many revealed fragmentation via development of a cone and vertical shear planes (Fig. 5A). A minority of samples did not fail via tension, instead failing via brittle shear, and this predominantly occurred in samples cured for 7 days; by 14 days the tensile failure mechanism had become established (samples containing PFA, also underwent this transition but only after a longer period of curing: 14 to 28 days, Royal et al. 2013). In addition, ‘beads’ of water were observed to form on the surface of a number of the 7 day samples, and, to a lesser extent, 14 day samples during UCS testing. The beads were observed to form, grow and then flow down the surface of the samples, pooling at the base, Fig. 5B. This phenomenon was not encountered with samples cured for the longer durations, nor was it observed in samples containing PFA as the major cement replacement material (Royal et al. 2013). It is not understood why this occurs with the juvenile samples containing GGBS, nor if this impacts upon the shear strength (or hydraulic conductivity) of the material and further research would be merited in this area.

The mean peak deviator stresses and the corresponding mean strains observed on the UCS are consistently lower than those encountered in TX-UU

(same datasets as presented in (a). PFA data represents mean trend for all samples at these curing and confining conditions previously reported by Royal et al. (2013). Both mixtures contained 200 g cementitious materials and 40 g bentonite per 1000 g of water

testing and the stiffnesses are greater (Fig. 3). Both sets of samples exhibit strain softening post peak deviator stress, although this behaviour varied with the application of confinement (Fig. 3). Strain softening in the TX-UU appeared to approach a constant strength (constant for the age of the sample, these values increased with curing), after approximately 3% strain. Conversely, the softening continued on the UCS (for the range of displacements considered). It is presumed that this is due to the failure mechanism encountered: without confinement the tension cracks readily dilate (once the cementitious bonds across the failure planes have sheared), reducing the frictional contacts between cone and fragments, and hence shear strength, between opposing faces of the shear planes; whereas the application of confining pressure provides resistance to the dilation of the fragmented sample, maintaining the frictional forces between the planes. The 90 day samples investigated on UCS appear to be significantly stronger and stiffer than the overarching trends might predict, conversely the 90 day samples confined at 200 kPa appear weaker than might be expected. It is believed that the behaviour of these samples is not illustrative of the overarching trends with curing and confinement but highlight the inherent difficulties when investigating samples batched from slurry.

The primary function of CBB is to retard ground-water flow; therefore the low hydraulic conductivity must be preserved. Development of microcracks within the fabric of the CBB prior to reaching the

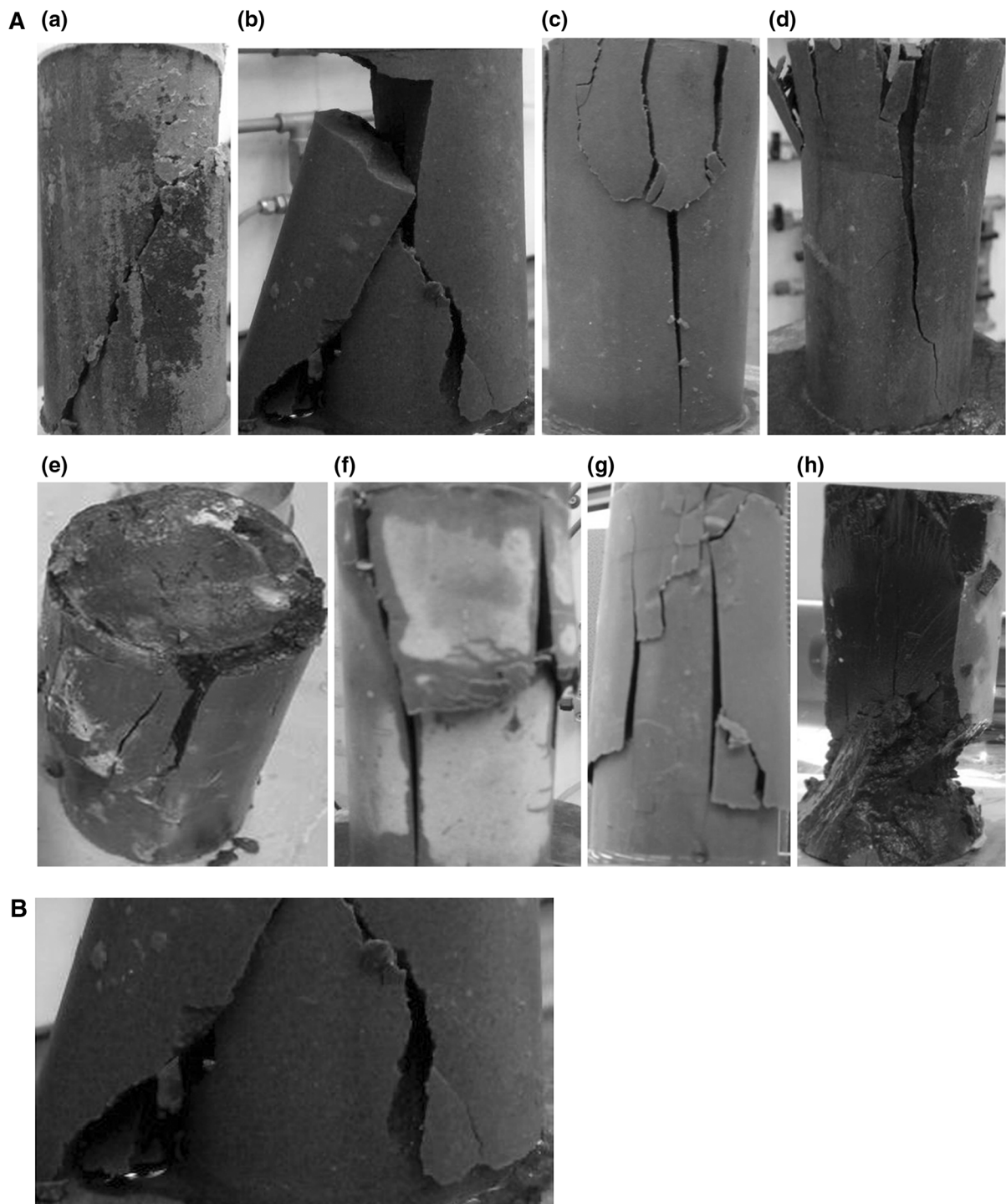


Fig. 5 **A** Sample failure mechanisms with duration of curing: **a** and **b** cured for 7 days and investigated using UCS; **c** and **d** cured for 14 days and investigated using UCS; **e** cured 28 days and investigated using the triaxial cell at 200 kPa confinement; **f** cured 60 days and investigated using UCS;

g cured 90 days and investigated using UCS; **h** cured for 90 days and investigated using the triaxial cell at 50 kPa confinement. **B** Evidence of water at base of sample (image taken from Fig. 5b), water was observed to ‘bead’ upon the surface of the sample before flowing down to the base

peak strength, due to deformation under undrained loading conditions, could potentially result in an increase in hydraulic conductivity and the compromising of the CBB performance. The development of microcracking in other cemented solids prior to reaching peak stress is well documented and there may be parallels between the behaviour of these materials and CB (Alzayani et al. 2016). Therefore, additional research is required to determine the extent of microcracking within CB prior to reaching the peak deviator stress and the consequences this will have on the hydraulic conductivity of CBB.

3.2 1D Compressibility with Curing

The compressibility of CB has previously been compared to overconsolidated soils (Opdyke and Evans 2005), due to the presence of what would

appear to be a preconsolidation pressure. Whilst the term preconsolidation pressure may be evocative of the compression response observed it does not satisfactorily describe the behaviour of the CB, which, like other cemented clay soils in anisotropic conditions, is a function of shearing the cemented bonds (Horpibulsuk et al. 2005). The compression behaviour of CB is related to a ‘critical threshold stress’: if this threshold is exceeded (and the cementitious bonds are sheared) then the settlements are significantly greater than those observed for stresses lower than the threshold stress. In order to estimate the magnitude of the threshold stresses Casagrande’s graphical method to approximate preconsolidation pressures has been used.

Each of the compression curves (Fig. 6) illustrates the presences of a threshold stress. The curing of the cementitious materials results in an increases in the magnitude of the threshold stress up to the 28 day

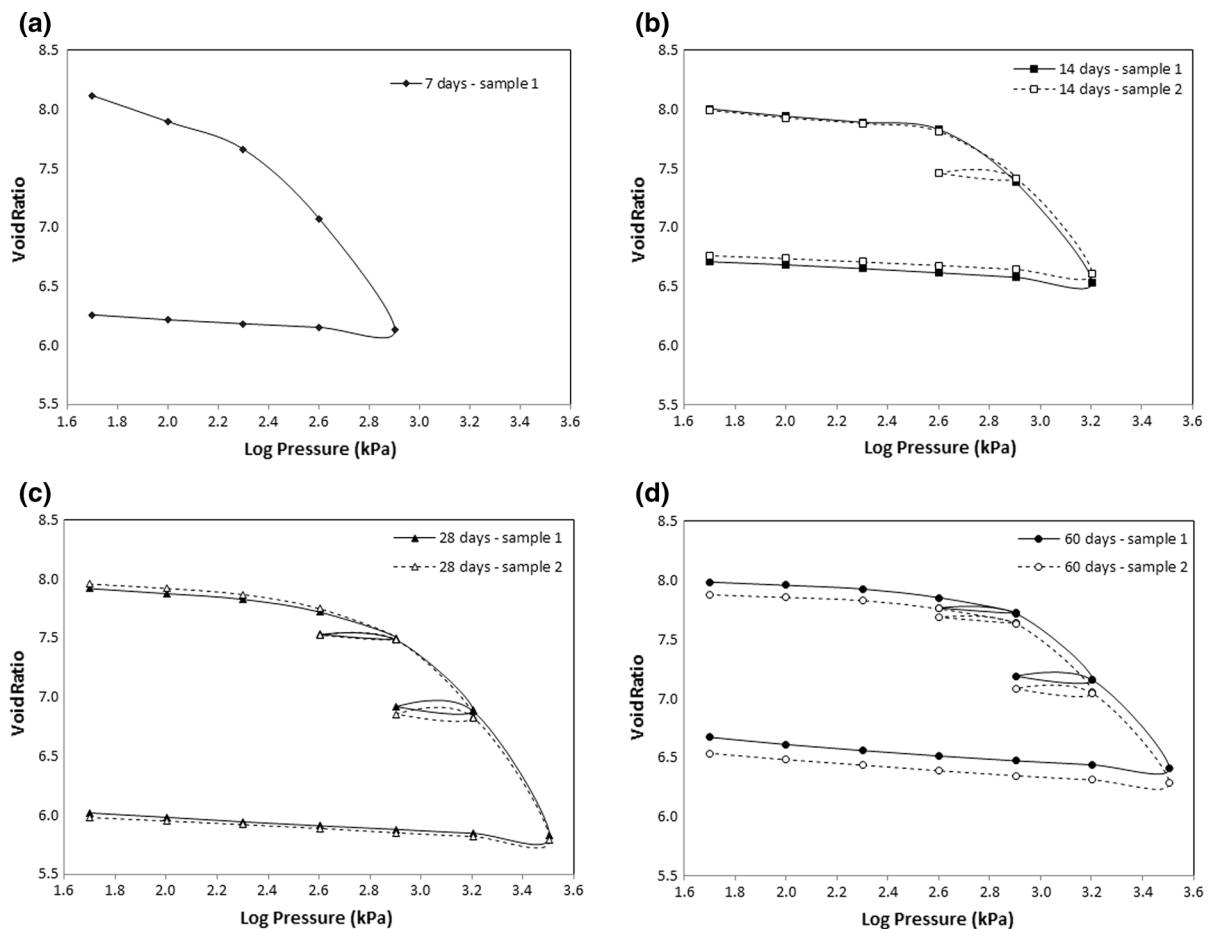


Fig. 6 Compression curves with duration of curing: **a** 7 days, **b** 14 days, **c** 28 days and **d** 60 days

samples, after which the threshold stress for the 28 and 60 day samples are very similar, suggesting that the threshold stress for the CB investigated approaches an asymptote (Table 2). Increased duration of curing also results in a slight reduction in the settlements observed once the threshold stress is exceeded and it is presumed that this is due to increased frictional forces (increased due to the development of cementitious products with curing) between the sheared cementitious products, as described by Mitchell and Soga (2005).

Application of loads below the threshold stress results in relatively small settlements associated with consolidation (Fig. 7): up to 0.5 mm in the 7 day sample and approximately 0.2 mm in the 60 day samples (equivalent to 2.6 and 1.1% of the original heights, respectively). Once the threshold stress was exceeded the material experienced significantly greater settlements (Fig. 7): up to 1.9 mm in the 7 day sample and approximately 1.6 mm in the 60 day samples (equivalent to 9.9 and 8.4% of the original heights, respectively). This significant increase in settlements indicates that the frictional contacts between the sheared cementitious products offers far less resistance to deformation and reflects the high void ratios associated with the CB.

3.2.1 Hydraulic Conductivity of the CB Derived Using the Oedometer

The approximate hydraulic conductivity values derived from the consolidation tests are observed to reduce both with the pressure applied and with curing, although the 7 day sample did not achieve the criteria for maximum hydraulic conductivity of 1×10^{-9} m/s regardless of load applied. The 14 and 28 day samples achieve the specification when loads greater than 100 and 50 kPa were applied, respectively, and 60 day samples achieved the specification regardless of load applied. Figure 8 illustrates reduction in hydraulic conductivity with load for the durations of curing considered, increasing load results in reduction in hydraulic conductivity, although there are localised increases in hydraulic conductivity at the 800 and 1600 kPa load steps. These variations occur when the samples return to the virgin compression line having experienced an unload-reload cycle, suggesting that the small elastic rebound associated with unloading

results in a small increase in the hydraulic conductivity of the material investigated.

3.3 Drying and Rewetting CB Containing GGBS

3.3.1 Drying the CB in an Oven for Short Periods

Drying the samples at a high temperature for short periods resulted in a reduction in water contents (up to 20%) and an obvious change of colour at the outer surface (grey, with the interior of the samples remaining dark green) indicating that the drying was localised. Had the samples been dried for longer it seems likely that the effects of the drying would have propagated into the centre until the samples were desiccated. Changes in the stress–strain response were observed on the UCS and found to be associated with duration of curing: samples cured for 7 or 14 days experienced increases in both peak strength and strain at failure when dried for up to 60 min, before experiencing reduction in both strength and strain at failure at 90 min drying (the strength was less than the control samples but the corresponding strains were larger). Conversely samples cured for 28 or 60 days experienced a reduction in mean strength with duration of drying but the mean strain at failure was observed to increase. The drying period was insufficient to induce desiccation cracking and rewetting the samples (for 3 h) resulted in a recovery of much of the lost water (water contents returned to approximately 3.0 to 3.5% of the original values prior to drying) and the stress–strain response was similar to samples cured for the same period but not exposed to the drying–rewetting phases (this was not the case for the 7 day samples, when rewetted these were stronger, and failed at smaller strains).

3.3.2 Drying the CB in Air (Samples Partially or Fully Exposed to Ambient Conditions)

Leaving the cured samples (Fig. 9a) in air (for 6 days) resulted in the expected drying and cracking of the samples (Fig. 9b). Rewetting these samples did not result in a closing of the cracks, supporting Jefferis' (2012) statement that cracking cannot be reversed by rewetting. The partial submergence of CB samples in saturated sand resulted in different behaviour to those dried in the air. The upper face exposed to the ambient conditions dried, cracked and experienced spalling

Table 2 Change in compression characteristics with curing

Age of sample at start of test (days)	Number of samples investigated	Maximum pressure applied (kPa)	[Initial/final/change]			Mean compression index (Cc)	Mean recompression index (Cs)	Approximate ^a mean threshold stress (kPa)	Mean peak deviator stress (kPa) ^b	Mean peak stress/mean threshold stress
			Mean void ratio	Mean dry density (kg/m ³)	Mean water content (%)					
7	1	800	8.52	270	338	0.59	–	288	343	1.2
			6.34	358	232					
			–2.17	88	–107					
14	2	1600	8.22	278	321	0.43	0.02	575	524	0.9
			6.79	332	265					
			–1.43	54	–57					
28	2	3200	8.01	281	317	0.57	0.01	833	639	0.8
			6.09	362	216					
			–1.92	81	–100					
60	2	3200	7.98	285	310	0.43	0.02	832	754	0.9
			6.70	351	223					
			–1.28	67	–87					

^a Estimated using Casagrande's graphical technique^b Mean value for samples investigated in the triaxial

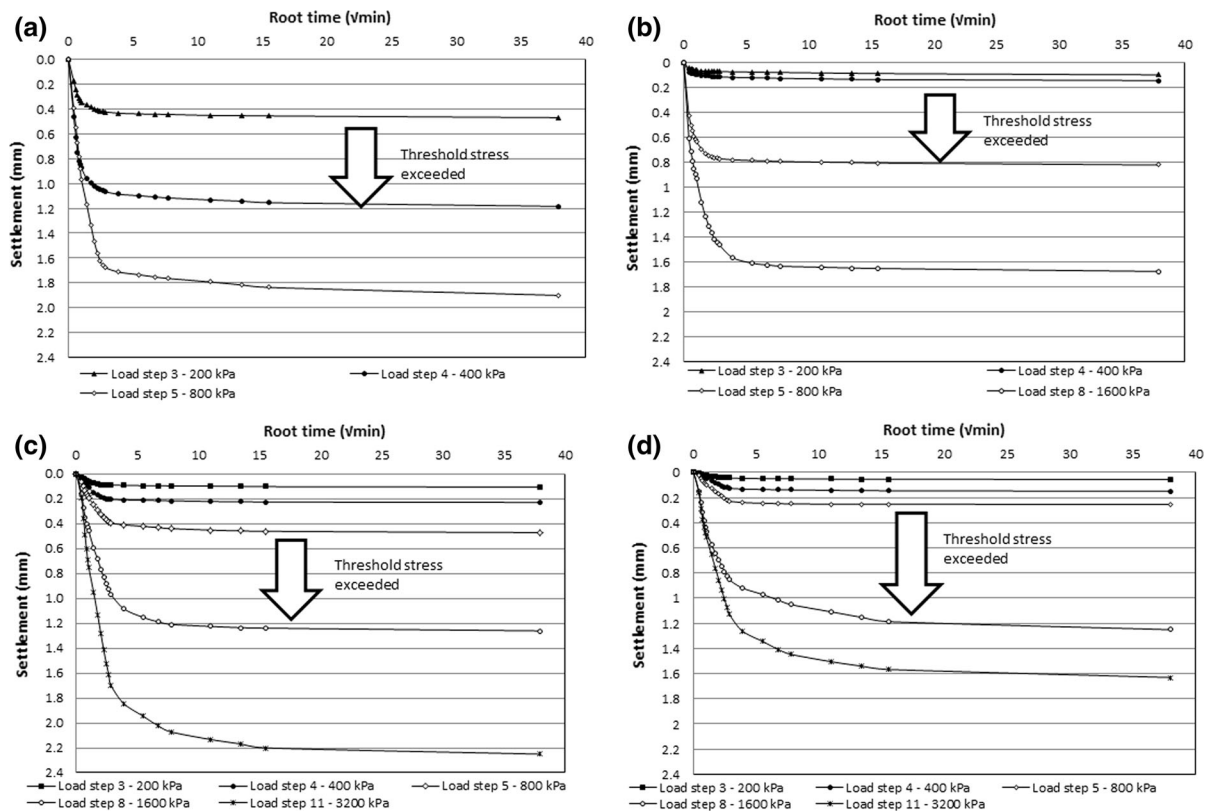


Fig. 7 Consolidation curves either side of the threshold stress: **a** 7 days, **b** 14 days—sample 2, **c** 28 days—sample 2 and **d** 60 days—sample 2

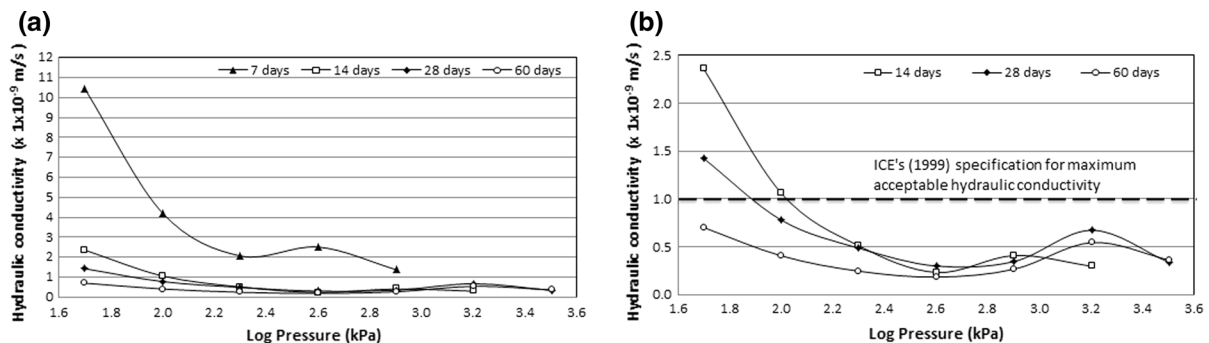


Fig. 8 Change in hydraulic conductivity with curing and loading (for the initial application of each load step, does not consider results of unload-reload cycles for the same loads) **a** for

the four time periods and **b** without the 7 day trend (illustrating the ICE (1999) criteria for hydraulic conductivity)

(Fig. 9c, d for 50 and 20% burial respectively). However, this only occurred a certain distance from the upper face (approximately 15 and 20 mm in Fig. 9c, d respectively), after this there was a graduated change in surface colour suggesting drying was slowly taking place as water migrated upwards

through the samples. This is particularly evident in Fig. 9c where the base of the sample appears to be similar to the colour of the control sample (Fig. 9a), although the unaffected depth is less than the length buried in the saturated sand suggesting that water is being drawn up through the sample towards the upper

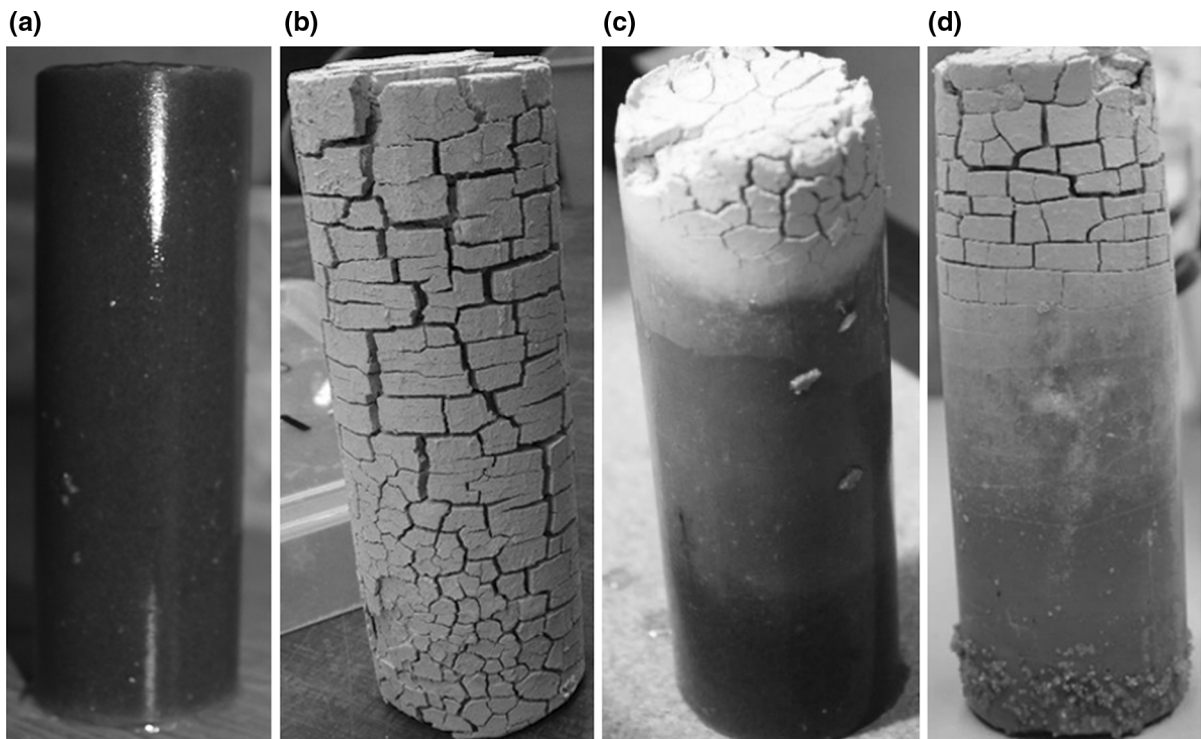


Fig. 9 Drying of CB samples: **a** CB sample taken directly from a water bath (not dried in the atmosphere), **b** 14 day sample exposed to the ambient conditions for 6 days, **c** 14 day sample with the lower half buried in saturated sand and the upper half

exposed to the atmosphere, and **d** 14 day sample with the lower 20% of the sample length buried in saturated sand and the upper 80% exposed to the atmosphere. The samples in **(c)** and **(d)** were exposed to these conditions for 28 days

face faster than water is permeating into the sample from the surrounding sand. It should be noted that increasing the duration of curing prior to placement of the samples within the sand resulted in slightly greater lengths of the sample drying and cracking; it is presumed that this may be due to the reduction in initial water content of the samples with curing. Soga et al. (2013) investigated a CB with a water content approximately 376% and notes that significant cracking had occurred by a water content of 275%. The mean water contents of the samples investigated decreased slightly with curing (348 to 332% for 7 and 60 days curing respectively) and it is possible that a reduction in water content of the older samples make them slightly more prone to drying, cracking and spalling in this experimental setup.

It has been suggested that exposure to air is a poor way to estimate CB Behaviour in situ and Joshi et al. (2008) embedded CB samples in a container filled with sand; the sand was exposed to 12 cycles of wetting and drying (3 days of wetting followed by 13 days of drying). The exhumed CB samples had

suffered discolouration on the outer surface (whitening) but the cracking commonly associated with drying were not evident. UCS test results indicate that the CB samples exposed to the cyclic wetting and drying were lower than those not exposed to these cycles suggesting that the CB had experienced physical changes whilst exposed to the cyclic wetting and drying (Joshi et al. 2008, suggest this might be due to microcracking). Joshi et al. (2008) state that the behaviour observed in the experiment was similar that of a barrier in situ, which had experienced fluctuations in the groundwater table yet not desiccated due to the presence of surrounding moist sand. This finding is contrary to the observations of Jefferis (2012) who cites observed cases of cracking that extend below the phreatic surface, and suggests that these barriers must have a capping layer applied as soon as possible to limit the loss of water through drying. Jefferis (2012) goes further to state that water loss through drying of an uncapped barrier is likely to be faster than water seeping into the barrier from the surrounding soil. The findings above would appear to validate Jefferis'

(2012) statement regarding drying of uncapped barriers.

These experiments were used to provide insight into how the CB behaved when dried, it is apparent that these tests were not sophisticated enough to provide any detailed understanding of the drying mechanisms or physico-chemical processes within the material and it is clear that additional research is required to determine how these barriers behave in the vadose zone.

4 Comparisons with Other CB Mixtures Containing GGBS Investigated on the UCS and Oedometer

A number of studies have considered the deformation behaviour of CB containing GGBS (Table 3, all mixes have been normalised to represent materials required per litre of water) and Fig. 10 summarises UCS from four such investigations. Figure 10 also presents a mixture containing PFA previously investigated by Royal et al. (2013) (containing the same total proportions of cementitious materials, bentonite and water). Direct comparison between the studies is problematic as different materials and mixture designs were used and some datasets represent mean values whereas others report single data points. However, from the descriptions of the CB mixes and the associated deformation response, it is possible to make a number of observations. Firstly, those datasets reporting

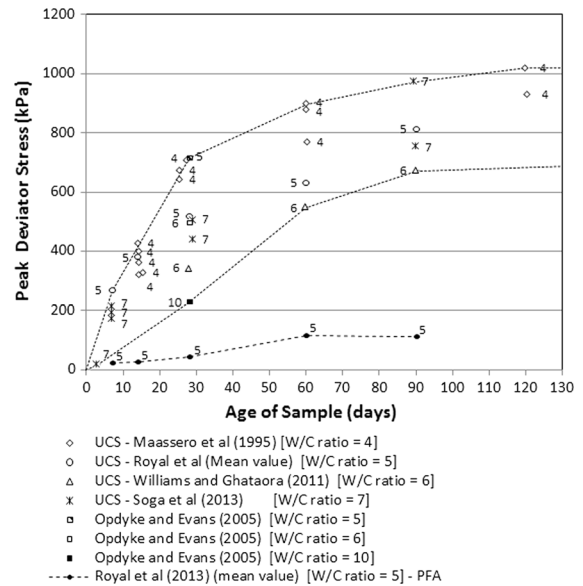


Fig. 10 Relationship between peak deviator stress in the UCS and age of samples (up to 130 days) containing GGBS for 7 CB mixes (number adjacent to symbol refers to the water/cement ratio). Note that the data for the CB containing PFA are mean for all of the samples investigated by Royal et al. (2013) at 50 kPa confining pressure, with the exception of the 90 day samples which is the mean response for the stronger three samples (the other samples being unexpectedly weaker—assumed to be related to issues with casting samples from a slurry). Data from Manassero et al. (1995) and Opdyke and Evans (2005) reproduced with permission from ASCE. Data from Soga et al. (2013) reproduced with permission from Taylor Francis. Data from Williams and Ghataora (2011) reproduced with permission from De Gruyter

Table 3 Approximated mixture proportions of CBs containing GGBS investigated in UCS

Investigators	Mass water (g)	Mass bentonite (g)	Mass cement (g)	Mass GGBS (g)	Total cementitious materials (g)	Proportion of GGBS	Water/cement ratio
Manassero et al. (1995)	1000	52	100	150	250	0.6	4
Royal et al. (current study)	1000	40	40	160	200	0.8	5
Opdyke and Evans (2005)	1000	53	42	168	211	0.8	5
Opdyke and Evans (2005)	1000	53	32	126	158	0.8	6
Williams and Ghataora (2011)	1000	37	32	128	161	0.8	6
Soga et al. (2013)	1000	40	30	120	150	0.8	7
Opdyke and Evans (2005)	1000	53	21	84	105	0.8	10

individual sample behaviour illustrate variation in peak deviator stresses with curing, as encountered in this study (Sect. 3.1), further highlighting potential difficulties when investigating CB mixes using a single sample approach and reinforcing the need to investigate duplicate samples, taking an average of the deformation response (or applying some form of statistical analysis). Secondly, there appears to be a relationship between water/cement (W/C) ratio and peak deviator stress, with increasing peak stresses achieved with lower W/C ratios (similar to the behaviour of concrete). Thirdly, rate of strength gain reduces with sample age (note that the boundaries applied are meant to encapsulate the range of responses whilst providing an illustration of overarching changes in strength with curing encountered with the combined data set and are not a prediction of strength with curing), with a significant proportion of the final strength achieved by 90 days. This suggests that investigations into long-term CB deformation behaviour would be more informative undertaken at 90 day curing rather than 28 days or earlier. Fourthly, the cement replacement materials (GGBS or PFA) have a significant impact upon the properties of the CB and care must be taken when developing the mixture design to ensure the desired performance criteria and physical properties (resistance to chemical degradation, etc.) are achieved.

Opdyke and Evans (2005) investigated a number of CB mixtures, using an air entraining cement with various proportions of GGBS (the mixture containing 20% cementitious materials at 80% GGBS

replacement, was found to be stronger than that investigated herein, Fig. 11), including one that was compressed in the oedometer. This mixture contained 15% cementitious materials (75% being GGBS), had a water/cement ratio of 6 (Table 3) and had cured for 15 months (Figs. 10, 11); it had an initial void ratio of 11.1, the threshold stress was estimated to lie between 100 and 200 kPa, the compression index was 0.97 and recompression index was 0.1 (Opdyke and Evans 2005). The mean peak stress (for the CB containing 15% cementitious materials) is estimated to be approximately 340 kPa (interpreted from the UCS trends presented in Fig. 11) hence, unlike the majority of samples investigated herein (Table 2), the mean peak stress was likely to be greater than the threshold stress. Therefore, should the threshold stress be formally considered within the specifications for CBB if there is the potential for the barrier to experience changes in loading conditions post hardening? A very strong material with low threshold stress may be an unsuitable material to use in a CBB that could be subjected to loading post hardening as a change in loading conditions sufficient to exceed the threshold stress could result in significant settlements, which may compromise the CBB. This could be particularly problematic if the changes in loading conditions are not applied uniformly along the length of the CBB resulting in differential settlements within the barrier; whilst the material may be able to resist the load (assuming it does not crack in undrained conditions) how does the CBB respond as the CB under the

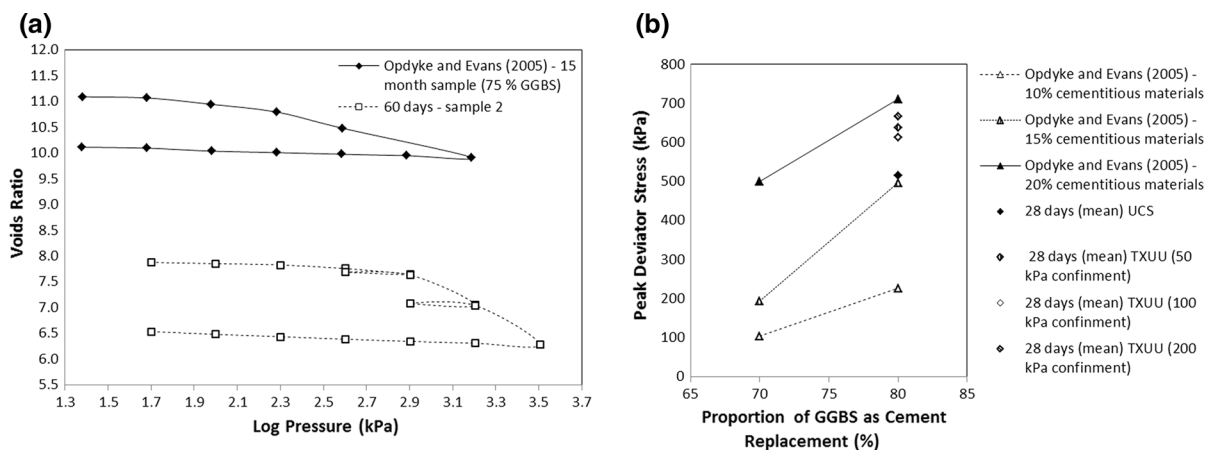


Fig. 11 **a** Comparison of compression curves for two CB mixtures, **b** peak deviator stresses encountered in UCS and TXUU. CB mixtures investigated by Opdyke and Evans' (2005) on

the UCS were cured for 28 days and deformed at 3 mm/min. Data from Opdyke and Evans (2005) reproduced with permission from ASCE

loading conditions compresses whilst material not experiencing the changes in loading does not? What happens at the interface between these loading environments, does the barrier material remain intact or will cracks develop? Furthermore how does the load distribution change with deformation (including interactions between the CBB and surrounding soil)? Clearly this requires additional research using larger scale experiments, where differential settlements can be investigated, or numerical analysis, than those used herein.

5 Conclusions

It is apparent that incorporation of GGBS into CB results in significantly stronger, stiffer materials than for those containing PFA, although the material containing GGBS would appear to perform comparatively poorly (when compared to a mixture without GGBS) if allowed to dry in the atmosphere. Furthermore, the outcomes from this study suggest that only specifying hydraulic conductivity and strength criteria may be insufficient when attempting to define the performance of the material. Whilst both are clearly important parameters attention should be given to how the material responds to change in loading conditions (compression response) or changes in groundwater regimes (i.e. changes in phreatic surface with time) to develop an understanding of how the CBB will function in situ. Therefore it is suggested that additional parameters should be considered, i.e. compressibility and drying-rewetting response, in addition to those currently specified (i.e. threshold stress should not be less than peak deviator stress, etc.).

Results of deformation response on the UCS and TX-UU indicate a non-linear increase in strength and stiffness up to the 90 day curing period, suggesting that investigation of CB cured for 90 days may provide more insight into long-term material properties than at 28 days. If undrained deformation response of CB is desired then it is suggested the TX-UU should be considered in preference to UCS as samples deformed on the USC (for the CB investigated) exhibited lower mean peak deviator stresses, at lower corresponding mean strains, resulting in higher estimated mean stiffness. The compression behaviour of the CB investigated is also a function of curing; the development of the cementitious bonds results in the

establishment of a threshold stress. The threshold stresses were observed to increase with curing up to 28 days, before a constant value appeared to be reached. Settlements induced by loads less than the threshold stress are relatively small as the cementitious products resist compression, although once the applied loads exceed the threshold stress, and the cemented bonds shear, the settlements are considerable. Evidence of previously investigated CBs containing GGBS where the 'threshold' stresses (found in 1D compressibility testing) may be lower than the deviator stress at peak strength suggests that this could result in significant settlements being induced within such a CBB if loaded (below peak strength but above the threshold stress) and, if experiencing differential loading conditions, could jeopardise the function of the barrier. Therefore it is suggested that compressibility of a proposed CB should be specified as a parameter in addition to the deformation response.

The drying of CBs in an oven illustrates that the mixture containing GGBS behaved fundamentally differently to one containing a blended cement (without GGBS); the CB containing GGBS dried, cracked and disintegrated whereas that without GGBS dried but did not (noticeably) crack nor disintegrate. Furthermore, the GGBS-CB exposed to ambient conditions also dried, cracked and disintegrated and these cracks would not heal when rewetted (which agrees with the findings of other investigations). This behaviour was also evident even when the material was partially submerged in saturated sand: the uppermost surface dried, cracked and disintegrated and it was clear that there was a vertical loss of water from the sample due to discolouration, even below the phreatic surface. This would appear to confirm the statement by Jefferis (2012) and suggests that the response of the CB in the vadose zone must be better understood.

Simple laboratory based experimentation is fundamental to understand the material behaviour of CB, although it is suggested that such tests do not provide sufficient information to understand how CBBs will behave in situ, which can be complex environments. Therefore it is suggested that additional research is required to further understanding of CBB behaviour using larger scale experimentation (where the CBB is buried in a surrounding soil) to better understand the behaviour of a CBB in ground conditions where it: is exposed to a fluctuating groundwater level; and where

it is loaded differentially (at magnitudes less than or greater than the threshold stress for the CB).

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